

Improved Human-Robot Teaming through Facilitated Initiative

Douglas A. Few, David J. Bruemmer, Miles C. Walton

Abstract—This paper evaluates collaborative tasking tools that facilitate dynamic sharing of responsibilities between robot and operator throughout a search and detection task. The goal is to arbitrate human and robot initiative such that the user can provide input at different levels without interfering with the robot's ability to navigate, avoid obstacles, plan global paths, and achieve task goals. A real-world search and detection experiment is used to compare Standard Shared Mode (SSM), where robot behavior unfolds from the robot's perception of its local environment and the attainment of task goals are the result of continuous operator supervision, to a Collaborative Tasking Mode (CTM), where operators input mission level tasks and the system dynamically constrains user and robot initiative based on the task element. Participants who utilize CTM do not experience a significant performance penalty, yet benefit from reduced workload and fewer instances of confusion. In addition, CTM participants report a higher overall feeling of control as compared to those using SSM.

I. INTRODUCTION

The Idaho National Laboratory (INL) has conducted a series of experiments over the past several years aimed at exploring the rich middle ground between direct human control and full robot autonomy [1-5]. While the benefits of robot initiative and intelligence have been demonstrated across all of these experiments, each experiment has also shown the potential for collaborative control to result in a struggle for control or a suboptimal task allocation between human and robot. In fact, the need for effective task allocation remains one of the most important challenges facing the field of human-robot interaction [6].

Even if the autonomous behaviors on-board the robot far exceed the human operator's ability, they will do no good if the human declines to use them or interferes with them. The fundamental difficulty is that human operators are by no means objective when assessing their own abilities [7-8]. In fact, an experiment which compared skilled robotic operators with novice users showed that novice users, who proved more willing to let the robot take initiative, often out-performed the skilled operators [1]. This same experiment also showed that operators do not always choose to use the mode of autonomy in which

they perform best. In the experiment, each operator performed four search operations. The first three operations were each accomplished with a different mode of autonomy. For the fourth operation, each participant was permitted to select a mode at will. Significantly, they rarely chose to use the mode of control in which they performed best and often chose the worst [1]. Even if users can accurately assess their own abilities, they often lack an understanding of the robot's level of proficiency and how their own input will affect overall performance. Another experiment shows that the operators who frequently override robot autonomy perform the worst overall [5]. It seems that leaving task allocation entirely up to the operator may be suboptimal.

The experiment discussed in this paper provides one example of how collaborative tasking tools and robot behavior tasking can be tailored to facilitate the process of dynamic task allocation. In particular, the system actually prevents human input at various stages of a search and detection operation, allowing the robot to take the leadership role over certain task elements including navigation, path planning and obstacle avoidance. The allocation of responsibilities embedded into the support tools and robot behavior options has been arrived at through prior HRI experiments which demonstrated that there are certain conditions where it is best to take control away from the human. The goal is not to force an arbitrary sharing of responsibility or authority, but rather to arrive at a *facilitative leadership* strategy that enhances the human – robot team's ability to adapt, solve problems, and improve performance [9]. This experiment examines how joystick bandwidth, cognitive workload, navigational error and overall task efficiency are affected by the introduction of behavior tasking that actually gives leadership



Figure 1: ATRV Mini

responsibility to the robot for various task elements. Assigning leadership roles to the robot is no trivial endeavor. If the process of dynamic task allocation is not handled correctly, the result will be a loss of flexibility and an increase in user frustration in addition to a reduction in performance. Consequently, this experiment

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Douglas A Few is with the Idaho National Laboratory, Idaho Falls, ID 83415 USA (phone: 208-526-3077; fax: 208-526-7688; e-mail: Douglas.few@inl.gov).

David J. Bruemmer is with the Idaho National Laboratory, Idaho Falls, ID 83415 USA. (e-mail: David.bruemmer@inl.gov).

Miles C Walton is with the Idaho National Laboratory, Idaho Falls, ID 83415 USA. (e-mail: Miles.walton@inl.gov).

is also concerned with the subjective question of how the user feels about their ability to appropriately influence the robot.

Mode of Autonomy	Defines Task Goals	Supervises Vehicle Direction	Motivates Motion	Prevents Collisions
Teleop	Human	Human	Human	Human
Safe	Human	Human	Human	Robot
SSM	Human	Human	Robot	Robot
CTM	Human	Robot	Robot	Robot

Figure 2: Initiative Chart

II. SYSTEM DESIGN

The INL control architecture is the product of an iterative development cycle where behaviors have been evaluated in the hands of users, modified, and tested again. The INL has developed a behavior architecture that can port to a variety of robot geometries and sensor suites. This architecture, called the Robot Intelligence Kernel, is being used as a standard by several HRI research teams throughout the community [10-13]. The experiments discussed in this paper utilized the iRobot “ATRV mini” shown in Figure 1.

The behavior architecture utilizes a variety of sensor information including inertial sensors, compass, wheel encoders, laser, computer vision, thermal camera, infrared break beams, tilt sensors, bump sensors, sonar, and ultrasonic sensors.

Using a technique described in [14], a *guarded motion* behavior permits the robot to take initiative to avoid collisions. In response to laser and sonar range sensing of nearby obstacles, the robot scales down its speed using an event horizon calculation, which measures the maximum speed the robot can safely travel in order to come to a stop approximately two inches from the obstacle. By scaling down the speed by many small increments, it is possible to insure that regardless of the commanded translational or rotational velocity, guarded motion will stop the robot at the same distance from an obstacle. This approach provides predictability and ensures minimal interference with the operator’s control of the vehicle. If the robot is being driven near an obstacle rather than directly towards it, *guarded motion* will not stop the robot, but may slow its speed according to the event horizon calculation.

Various modes of control are available from the interface [1,2], affording the robot different types of behavior and levels of autonomy (see figure 2). These modes include *Teleoperation* where the robot takes no initiative, *Safe Teleoperation* where the robot takes initiative only to protect itself, *Standard Shared* where the human and robot may both take initiative and *Collaborative Tasking* where aside from the ability to abort missions, no human input is accepted after a mission is given. Of these modes, the experiment discussed in this paper focused on *Standard Shared Mode* and *Collaborative Tasking*. *Standard Shared Mode* is discussed in several previous experiments [1, 2, 5] and

allows the human to override robot initiative at any time. Collaborative tasking includes new tools that provide a means to share information about the task and environment and use this input to moderate human and robot initiative. Note that the system is designed not necessarily to insure an equal sharing of control and authority, but rather to optimize overall performance.

Throughout several previous experiments, *Standard Shared Mode (SSM)*, has provided a means for the robot to relieve the operator from the burden of direct control, using reactive navigation to find a path based on perception of the environment. In SSM, the robot accepts operator intervention in the form of intermittent directional commands and supports dialogue through the use of a finite number of scripted suggestions (e.g. “Path blocked! Continue left or right?”) and other text messages that appear in a text box within the graphical interface. In SSM, the operator may override the translational and/or rotational behavior of the robot at any time by moving the joystick. As one might expect, some SSM users supply only intermittent directional input, while others constantly override the robot initiative.

This experiment evaluates the effectiveness of new user tasking functionality where the system explicitly facilitates sharing to insure an efficient allocation of responsibilities. To investigate the utility of these collaborative tasking tools, this experiment examines a search task where half of the operators use SSM and the remaining operators use *Collaborative Tasking Mode (CTM)*, which includes the new tasking tools.

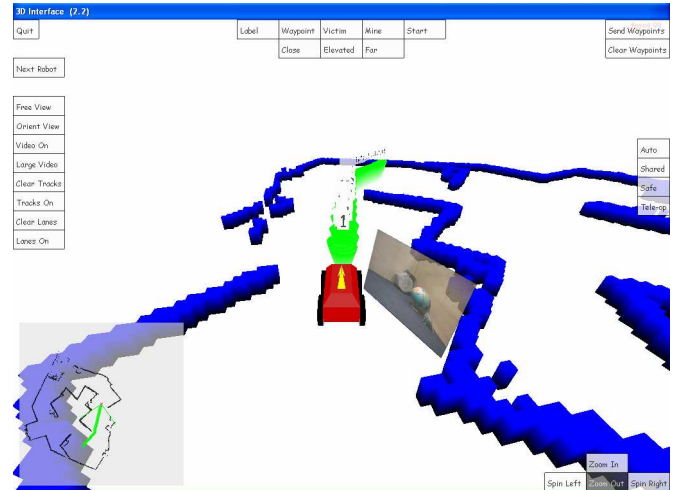


Figure 3: 3D Interface View while engaged in a collaborative task

The premise behind the design of CTM was that the robot is better at navigating throughout an environment, but that the human is better at maneuvering the robot to gain situation awareness once a targeted location is reached. Consequently, the CTM mode was structured to give the robot the leadership role over navigation and path planning, whereas the human retains the leadership role over the robot’s behavior once a targeted area of interest has been reached. Also, the human retains the leadership role over the initial tasking (i.e. specifying an area of interest) and, throughout the task, remains in full control of the payload – a visual camera with pan, tilt and zoom

capabilities. One of the tasking tools used for this experiment is a 3D augmented-virtuality interface designed by Nielsen [12] as shown in Figure 3. In the 3D interface, the green cones communicate the proposed path to a target location identified by the user. As the robot travels along the proposed path the cones are *consumed* enabling the operator to ascertain the success of the robot with respect to its reasoned strategy. In addition, representing the progress to the remote operator through the consumption of cones, the robot keeps track of its progress to the goal. If dynamic changes in the environment result in insufficient progress to the goal, the robot replans a route from its current position. The replanned route gets communicated to the human by updating the green cones within the 3D virtual environment.

It is important to note that even when the operator does not have the ability to directly control robot movement, the collaborative tasking tools provide insight to the intentions of the automaton thereby supporting the ability of the operator to initiate and abort the various robot behaviors. The collaborative tasking tools are not designed to strip control from the human, but rather provide an efficient method of delegation. Moreover, the collaborative tasking tools allow the user input on how the robot approaches the delegated task. For instance, one user might set down intermediary goal points, while another may permit the robot to autonomously path plan from one end of the room to another

III. EXPERIMENT

Results from prior HRI experiments demonstrate SSM to be more effective in terms of task efficiency, workload and the users feeling of control when compared to *Safe Teleoperation Mode (STM)*; however observation showed the cognitive burden of using SSM was still too great to facilitate the simultaneous operation of the robot and robot payloads. In order to address the limitations observed, a suite of collaborative tasking tools which should allow operators to task the robot with respect to the overall mission goals was needed.

In response to the observed HRI needs, work began at the INL to develop collaborative tasking tools which would allow the user to create paths, search areas, or go to points by simply clicking in the map. These collaborative tasking tools required a combined coordination between robot capability and interface intelligence. In particular, the goal was to determine if a toolset could be developed to increase task efficiency and the operator's feeling of control while reducing the cognitive burden or remote system deployment.

A. Participants

The experiment was performed over a seven-day period at the St. Louis Science Center and involved 32 volunteers. The majority of participants were high school students from schools in the St. Louis area. These students were not pre-selected, but rather volunteered to take part in the study while visiting the Science Center. The Mean age of all the participants was 19.03 years old with a

median and mode of 18 years old. There were no significant age differences, $F(1, 31) = 0.4279$, $p = 0.059$ in the average age between the participating groups, $M = 19.06667$ and $M = 19.00$ for the *SSM* group and *CTM* group respectively.

B. Procedure

The experiment was set up as a remote deployment such that the operator control station was located several stories above the robot arena so that the operator could not see the robot or the operational environment. The production staff of the Science Center used plywood dividers and a variety of objects such as artificial rocks and trees to create a 50ft x 50ft environment with over 2000 square feet of navigable space (see Figure 4). Each participant was given basic instructions on how to use the interface, and no participants were permitted to control the robot prior to the start of their trial run. Participants were assigned to alternating conditions so as to ensure equal numbers of participants in each condition. No participant was allowed to operate the robot in more than one trial. Each trial run was executed to completion or until the participant voluntarily withdrew. In no case did a participant withdraw.



Figure 4: *a priori* map

Prior to each run, a map of the remote environment was created by the robot such that the participant could correlate the robot's position in its map to an *a priori* map (Figure 3) given as a tool for the assigned task. Each participant was told to direct the robot around the environment and identify items (e.g. dinosaurs, a skull, brass lamp, or building blocks) located at the numbers represented on a paper *a priori* map. In addition to identifying items, the participants were instructed to navigate the robot back to the Start/Finish to complete the loop around the remote area. This task was selected because it forced the participants to navigate the robot as well as use the camera controls to identify items at particular points along the path. The items were purposely located in a logical succession in an effort to minimize the affect of differences in the participants' route planning skills. In no case did a participant attempt to identify the objects out of numerical sequence.

In addition to the primary task of navigating and identifying objects the participants were asked to simultaneously conduct a secondary task which consisted of answering a series of basic two-digit addition problems on an adjacent computer screen. The participants were told the problem would appear on the screen periodically and their presence would be announced by a tone. The process of responding to the math problems was demonstrated to each participant. The participants were instructed to answer the questions to the best of their ability but told that they could skip a problem by hitting the <enter> key if they realized a problem appeared but felt they were too engaged in robot control to answer. Additionally, participants were told a problem would be considered “ignored” if the primary task completed and a secondary task was awaiting a response. The first addition problem triggered thirty seconds into the trial. Each problem remained present until it was responded to, or the primary task ended. Thirty seconds after a participant’s response, a new addition problem would be triggered. The secondary task application recorded time to respond, in seconds, as well as the accuracy of the response and whether the question was skipped or ignored.

All participants were given access to the same interface (see Figure 3) within which the robot’s position is represented in the map it builds as it explores new territory. Exactly half of the participants used *Standard Shared Mode* to navigate the robot to identify items at the specified locations, whereas the other participants controlled the robot in the *Collaborative Tasking Mode* selecting positions in the map for the robot to “go to” and identified the items by controlling the robot’s camera or by manually maneuvering the robot to bring items into view.

During each trial, the interface stored a variety of useful information about the participant’s interactions with the interface. For instance, the interface recorded the time to complete the task to be used as a metric of the efficiency between the methods of control. For the CTM participants, the interface also recorded the portion of time the robot was available for direct control. The interface recorded the number of joystick vibrations caused by the participant instructing the robot to move in a direction in which it was not physically possible to move. The number of joystick vibrations represents losses of situation awareness as the operator commanded the robot in a direction already articulated, via the GUI interface, as not passable. The overall joystick bandwidth was also logged to quantify the amount of joystick usage. Immediately after completing a trial, each participant was asked to rank on a scale of 1 to 10 how “in control” they felt during the operation, where 1 signified “The robot did nothing that I wanted it to do” and 10 signified, “The robot did everything I wanted it to do.”

C. Results

All participants completed the assigned task. Analysis of the time to complete the task showed no statistically significant difference between the SSM and CTM groups. On average, SSM participants completed the task slightly

faster than their CTM counterparts with $M = 308.6$ seconds, $M = 332.4$ seconds, respectively. The difference, however, was not of significance between the sample sets $F(1,31) = 1.758$, $p = 0.139$. Following the experiment it was discovered that while engaged in a collaborative task the robot’s upper speed was bound at 0.3 meters/sec whereas SSM allowed the robot to reach speed up to 0.6 meters/sec. In both cases the actual speed of the robot is calculated using the method described in Pacis et al [14] however the difference in the upper bound may account for the time to task completion difference. Future work will further explore the primary efficiency of the interaction modes.

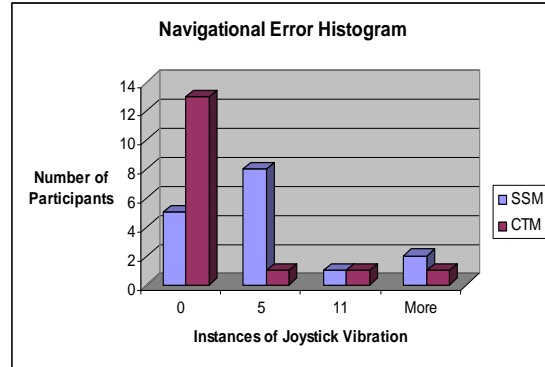


Figure 5: Navigational Error Comparison

An analysis of human navigational error showed that 81% of participants using CTM experienced no instances of operator confusion as compared to 33% for the SSM participants. Figure 5 shows a comparison of navigational error by mode. Overall, SSM participants logged a total of 59 instances of operator confusion as compared with only 27 for the CTM group. The mean average was 3.93 for the SSM group and 1.59 for the CTM group, although the lack of a Gaussian distribution for either group diminishes the statistical significance of the mean averages or of a standard F test. The median for CTM was 0 as compared with a median of 2 for the SSM mode.

Overall, CTM participants collectively answered 102 math questions, while the SSM participants answered only 58. Of questions answered, CTM participants answered 89.2% correctly as compared to 72.4% answered correctly by participants using SSM. To further assess the ability of SSM and CTM participants to answer secondary task questions an analysis was performed on the average response time for each group. CTM participants had an average response time of 25.1 seconds as compared to 49.2 seconds for those using SSM. This difference was statistically significant $F(1,31) = 2.148$, $p < 0.05$. Together these results indicate that the participants using the collaborative tasking tools experienced a substantial decrease in the required workload to complete the task. In addition, CTM participants enjoyed a higher overall *feeling of control* as compared to SSM participants $M = 8.53$ and $M = 6.73$ respectively, $F(1,31) = 3.22$, $p < 0.05$ (see Figure 6 below).

D. Discussion

Participants who utilized CTM suffered no performance penalties with respect to overall mission efficiency, yet they had fewer instances of navigational error, performed significantly better on the secondary task, and enjoyed a higher *feeling of control*. These findings indicate that it is possible to create a toolset that constrains the human's responsibilities and authority, but does not undermine their ability to perform or their trust in the system.

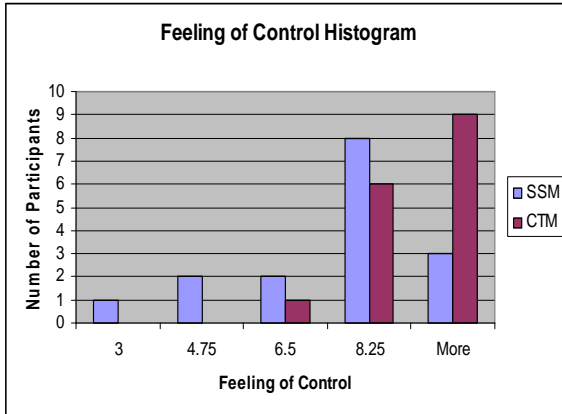


Figure 6 Feeling of Control Comparison

Previous studies with the Robot Intelligence Kernel showed that participants using SSM had, on average, fewer instances of navigational error, less joystick usage and a higher feeling of control than those using *Safe Teleoperation Mode*, where the human was responsible for directly controlling the robot. Despite these benefits, the previous studies had shown that many users of the so called “Shared” mode, in fact, shared very little. Without a means to explicitly facilitate the allocation of responsibilities between human and robot, some users shared control effectively while others did not. The collaborative tasking mode evaluated in this paper provides this means to facilitate an effective sharing of responsibilities.

In fact, the participants in the CTM group spent, on average, 42.0% of the mission duration with the robot in the leadership role, during which time joystick commands were ignored. In contrast, SSM participants may supply joystick input at any time. On the other hand, CTM does not dictate exactly how much control or input the operator has. The CTM participants in this study varied significantly in terms of how much time each user spent in the leadership role. For example, one participant successfully completed the task having yielded 61.9% of the mission duration to the robot's control.

Interestingly, it seems that although the facilitative task allocation provided by the collaborative tasking tools greatly reduced human workload and instances of navigational error, there remains a subset of participants who refuse to use the system as it was intended and attempt to maximize their own input. A more in-depth review of the data showed that only three participants experienced any navigational error in the CTM group and

that these three had a disproportionate amount of joystick bandwidth. The average total joystick bandwidth of the members of the CTM group who experienced no instances of navigational error was $M = 95.92$. The three CTM participants who did experience navigational error had total joystick bandwidth values well outside three standard deviations of the average joystick bandwidth for the rest of the group. Future work is necessary to address the fundamental question of why there remains a subset of the population who insist on taking manual control of the robot despite the available toolsets.

IV. CONCLUSION

This experiment provides validation of the collaborative tasking tools that have been implemented as part of the Robot Intelligence Kernel. The experiment showed that from an engineering perspective, the blending of guarded motion, reactive obstacle avoidance and global path planning behaviors on board the robot can be used effectively to accomplish a search and detection task. Of greater significance to the Human-Robot Interaction community is the fact that this experiment represents a definitive step away from the supervisory control paradigm where the human may accept or decline robot initiative, while remaining at all times in the leadership role for all task elements. Instead, the collaborative tasking tools presented here arbitrate leadership in a facilitative manner to optimize overall team performance.

In SSM, overall team performance can benefit from the robot's understanding of the environment, but can suffer because the robot does not have insight into the task or the user's intentions. For example, in SSM, the robot may take the path of least resistance around an obstacle, not understanding that this route takes the robot out of the room that the user wishes to explore. As a result, the human must override the robot, which reduces efficiency, increases human workload and may also increase user distrust or confusion. Instead, the CTM interface tools provide the human with a means to communicate information about the task goals. The benefit of the collaborative tasking tools is not merely the benefit of increased autonomy, but rather the fact that they permit the human and robot to mesh their understanding of the environment and task. Based on this combined understanding of the environment and task, CTM is able to arbitrate responsibility and authority. By constraining operator initiative at the right times, CTM reduces human confusion and frustration. CTM actually increases users' feeling of control by taking control away from them. Although the Human-Robot Interaction community has long used the phrase “mixed initiative” to describe the goal of team members blending their input together. The findings of this paper imply that rather than “mixing” initiative, human-robot teaming may benefit when initiative is “facilitated” to avoid conflict and optimize task allocation.

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